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Studies of radiative $X(3872)$ decays at Belle

VISHAL BHARDWAJ (FOR THE BELLE COLLABORATION)

*Physics Department
Nara Women's University,
Kitauoya Nishi-machi, Nara, Japan -630 8506.*

We present a study of the radiative decays of $X(3872)$ at Belle. In the $\chi_{c1}\gamma$ final state, we got the first evidence of a new particle at $3823 \text{ MeV}/c^2$.

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1 Introduction

The Belle detector is a general purpose spectrometer built to test the Standard Model mechanism for CP -violation in B decays to charmonium (golden channel) [1]. Parallel to this, Belle has proven to be an ideal place to carry out charmonium spectroscopy thanks to its very clean environment. Many new $c\bar{c}$ and $c\bar{c}$ -like exotic candidates states such as $\eta_c(2S)$, $X(3872)$, $X(3915)$, $Z(3930)$, $X(3940)$, $Z_1(4050)^+$, $Z_2(4250)^+$, $Y(4260)$, $Z(4430)^+$ and $Y(4660)$ have been found. Among them $X(3872)$ is the most interesting state which was first observed in $B^\pm \rightarrow (J/\psi\pi^+\pi^-)K^\pm$ at Belle [2]. Soon after its discovery, it was confirmed by the CDF [3], D0 [4] and BaBar [5] collaborations. Recently, it has also been observed at LHCb [6] and CMS [7]. The observation of $X(3872)$ in the same final states $(J/\psi\pi^+\pi^-)$ in six different experiments, reflects the eminent status of the $X(3872)$. $X(3872)$'s narrow width and the proximity of its mass, $3871.7 \pm 0.2 \text{ MeV}/c^2$ to the $D^{*0}\bar{D}^0$ threshold makes it a good candidate for a $D\bar{D}^*$ molecule [8]. Other possibilities have also been proposed for the $X(3872)$ state, such as tetraquark [9], $c\bar{c}g$ hybrid meson [10] and vector glueball models [11].

Radiative decays of $X(3872)$ provide a unique opportunity to understand the nature of $X(3872)$. For example, $X(3872) \rightarrow J/\psi\gamma$ resulted in the confirmation of C -even ($C = +$) parity for $X(3872)$ [12, 13, 14]. A similar decay mode $X(3872) \rightarrow \psi'\gamma$ can help to identify $X(3872)$ as a charmonium, molecular or mixture of those states [8, 15, 16]. Belle reported no significant signal [14] and it disagrees with the evidence at BaBar [13].

A recent search for the charged tetraquark partner of $X(3872)(\rightarrow J/\psi\pi^+\pi^0)$ gave negative results [17]. But still it is hard to totally rule out $X(3872)$ as a tetraquark, as some tetraquark models predict $X(3872)^+$ to be broad, thus still difficult to observe at current statistics [18]. On the other hand, in both molecular and tetraquark hypothesis a C -odd parity ($C = -$) partner can exist and it may dominantly decay into $\chi_{c1}\gamma$ and $\chi_{c2}\gamma$ final states. Partner searches would be another approach to reveal $X(3872)$ structure. Along with this, undiscovered 3D_2 charmonium (ψ_2) is expected to have a significant branching fraction to $\chi_{c1}\gamma$ and $\chi_{c2}\gamma$ [19, 20]. In this report, we also describe the first evidence of $\psi_2 \rightarrow \chi_{c1}\gamma$ decay.

2 Reconstruction

B mesons reconstructed using $B^\pm \rightarrow (\chi_{c1}(\rightarrow J/\psi\gamma)\gamma)K^\pm$ and $B^\pm \rightarrow (\chi_{c2}(\rightarrow J/\psi\gamma)\gamma)K^\pm$ decay modes are used in the search for C -odd partner of the $X(3872)$ and other new narrow resonances. The results presented here are obtained from a data sample of $772 \times 10^6 \text{ } B\bar{B}$ events collected by the Belle detector [21] at the KEKB [22] energy-asymmetric e^+e^- collider operating at the $\Upsilon(4S)$ resonance.

The J/ψ meson is reconstructed in its decays to $\ell^+\ell^-$ ($\ell = e$ or μ). In e^+e^- decays,

the four-momenta of all photons within 50 mrad of each of the original e^+ or e^- tracks are included in the invariant mass calculation [hereafter denoted as $M_{e^+e^-(\gamma)}$], in order to reduce the radiative tail. The reconstructed invariant mass of the J/ψ candidates is required to satisfy $2.95 < M_{e^+e^-(\gamma)} < 3.13 \text{ GeV}/c^2$ or $3.03 < M_{\mu^+\mu^-} < 3.13 \text{ GeV}/c^2$. A mass- and vertex-constrained fit is applied to all the selected J/ψ candidates in order to improve their momentum resolution. The $\chi_{c1,2}$ candidates are reconstructed by combining J/ψ candidates with a photon having energy (E_γ) greater than 200 MeV. The photons are reconstructed from the energy deposition in electromagnetic calorimeter. To reduce the background from $\pi^0 \rightarrow \gamma\gamma$, we calculate a likelihood function to distinguish an isolated photon from π^0 decays using the photon pair's invariant mass, smaller photon's laboratory energy and polar angle [23]. Then we reject a photon having the π^0 likelihood ratio greater than 0.7 by combining with any other photon. The reconstructed invariant mass of χ_{c1} and χ_{c2} is required to satisfy $3.467 < M_{J/\psi\gamma} < 3.535 \text{ GeV}/c^2$ and $3.535 < M_{J/\psi\gamma} < 3.611 \text{ GeV}/c^2$. A mass- and vertex-constrained fit is again performed to all the selected χ_{c1} and χ_{c2} candidates in order to improve their momentum resolution. Charged tracks are identified as a kaon using information from the particle identification devices.

To reconstruct the B candidates, each χ_{c1} , χ_{c2} is combined with a kaon candidate and an additional photon having $E_\gamma > 100 \text{ MeV}$. In this additional photon selection, we reject the photon which in combination with another photon in that event, gives mass in the region around π^0 mass defined as $117 < M_{\gamma\gamma} < 153 \text{ MeV}/c^2$. In order to remove the reflection of photons coming from χ_{c1} and χ_{c2} decays, we reject the best χ_{c1} or χ_{c2} daughter photon from the additional photon list to form a B candidate. To identify the B candidate, two kinematic variables are used : energy difference $\Delta E \equiv E_B^* - E_{beam}^*$ and beam-energy constrained mass $M_{bc} \equiv \sqrt{(E_{beam}^*)^2 - (p_B^{cms})^2}$, where E_B^* is the center-of-mass frame (cms) beam energy, and E_B^* and p_B^* are the cms energy and momentum of the reconstructed particles. In case of multiple candidates, ΔE closest to 0 is selected as the best one. Invariant mass of the final state ($M_{\chi_{c1}\gamma}$ and $M_{\chi_{c2}\gamma}$) is used to identify the resonance. In order to improve the resolution of $M_{\chi_{cx}\gamma}$ [24], we scale the energy of γ to make ΔE equal to zero.

To suppress continuum background, events having a ratio of the second to zeroth Fox-Wolfram moments [25] $R_2 > 0.5$ are rejected. Large $B \rightarrow J/\psi X$ MC samples (corresponding to 100 times the data sample size used in this analysis) are used to study the background. The non- J/ψ (non- $\chi_{cx\gamma}$) background is studied using the $M_{\ell\ell}$ ($M_{J/\psi\gamma}$) sidebands in data. $B^\pm \rightarrow (\chi_{c1}\gamma)K^\pm$ and $B^\pm \rightarrow (\chi_{c2}\gamma)K^\pm$ yields are extracted from a 2D UML fit applied to the distribution in the $M_{\chi_{cx}\gamma}$ - M_{bc} space.

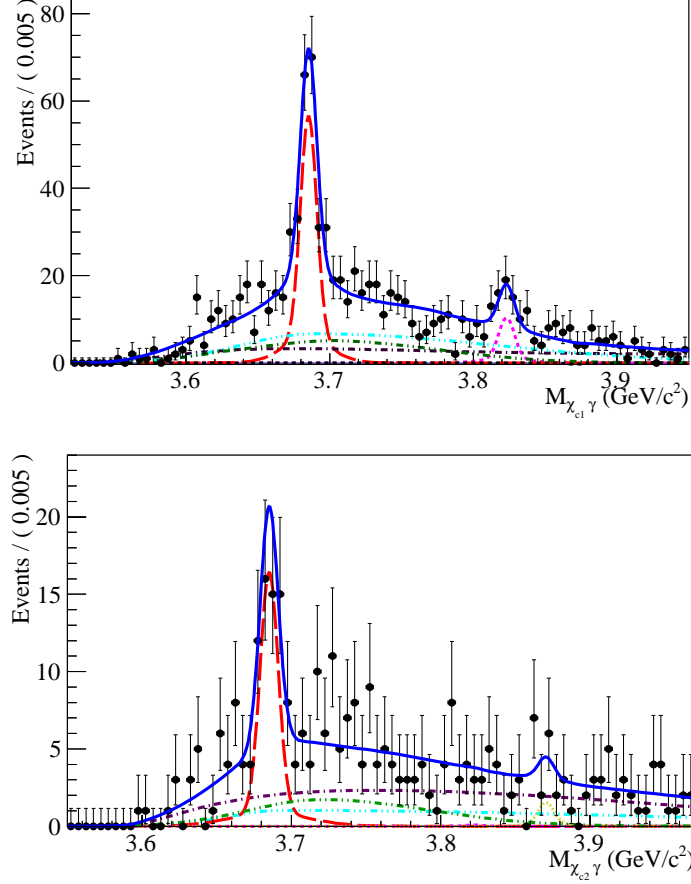


Figure 1: 2D UML fit projections in $M_{\chi_{c1}\gamma}$ (top) and $M_{\chi_{c2}\gamma}$ (bottom) for the signal region $M_{bc} > 5.27 \text{ GeV}/c^2$. The curves show the signal [red large-dashed for ψ' , pink dashed for ψ_2 and yellow dotted for $X(3872)$] and the background component [purple dotted-dashed for combinatorial, dark green two dotted-dashed for $B^\pm \rightarrow \psi'$ (other than $\chi_{c1}\gamma$) K^\pm and cyan three dotted-dashed for peaking component] as well as the overall fit [blue solid].

3 Results

In $B^\pm \rightarrow (\chi_{c1}\gamma)K^\pm$ decay, a clear peak of $\psi' \rightarrow \chi_{c1}\gamma$ is observed in the $\chi_{c1}\gamma$ invariant mass ($M_{\chi_{c1}\gamma}$) projection. In addition to this, we also find clear evidence of a narrow peak at $3823 \text{ MeV}/c^2$, denoted as $X(3820)$ hereafter. Since statistics are still limited, its width is poorly constrained to be $4 \pm 6 \text{ MeV}$ even if it is floated in the fit. Therefore we set $X(3820)$ natural width to be 0 MeV for further discussion. We estimate the statistical significance of $X(3820) \rightarrow \chi_{c1}\gamma$ to be 4.2σ including systematic uncertainty. In our search for $X(3872) \rightarrow \chi_{c1}\gamma$, no signal is seen and 90% confidence level (C.L.)

Channel	Yield	$\mathcal{B}(10^{-4})$
$B^\pm \rightarrow \psi'(\rightarrow \chi_{c1}\gamma)K^\pm$	$193.2^{+19.2}_{-18.6}$	$7.7^{+0.8+0.9}_{-0.7-0.8}$
$B^\pm \rightarrow \psi'(\rightarrow \chi_{c2}\gamma)K^\pm$	$59.1^{+8.4}_{-8.0}$	$6.3 \pm 0.9 \pm 0.6$
		$\times 10^{-6}$
$B^\pm \rightarrow X(3820)(\rightarrow \chi_{c1}\gamma)K^\pm$	$33.2^{+9.2}_{-8.5}$	$9.7^{+2.8+1.1}_{-2.5-1.0}$
$B^\pm \rightarrow X(3872)(\rightarrow \chi_{c1}\gamma)K^\pm$	-0.9 ± 5.1	< 2.0
$B^\pm \rightarrow X(3820)(\rightarrow \chi_{c2}\gamma)K^\pm$	$0.3^{+3.9}_{-3.1}$	< 3.6
$B^\pm \rightarrow X(3872)(\rightarrow \chi_{c2}\gamma)K^\pm$	$4.7^{+4.4}_{-3.6}$	< 6.7

Table 1: Summary of the results. Measured \mathcal{B} (with 90% confidence level (C.L.) upper limit (U.L.) for $B^\pm \rightarrow X(3872)(\rightarrow \chi_{c1}\gamma)K^\pm$, $B^\pm \rightarrow X(3823)(\rightarrow \chi_{c2}\gamma)K^\pm$ and $B^\pm \rightarrow X(3872)(\rightarrow \chi_{c2}\gamma)K^\pm$ decay modes). \mathcal{B} for $B \rightarrow XK$ is $\mathcal{B}(B \rightarrow XK)\mathcal{B}(X \rightarrow \chi_{c\alpha}\gamma)$, here X stands for $X(3820)$ and $X(3872)$. For \mathcal{B} , the first (second) error is statistical (systematic).

upper limit (U.L.) on $\mathcal{B}(B^\pm \rightarrow X(3872)K^\pm)\mathcal{B}(X(3872) \rightarrow \chi_{c1}\gamma)$ is estimated using a frequentist approach. In $B^\pm \rightarrow (\chi_{c2}\gamma)K^\pm$, we observe a clear peak of the $\psi' \rightarrow \chi_{c2}\gamma$. However, we do not see any hint of a narrow resonance with the current statistics. Figure 1 shows the projections of 2D UML fits to the $M_{\chi_{c1}\gamma}$ and $M_{\chi_{c2}\gamma}$ cases for the signal region, $M_{bc} > 5.27 \text{ GeV}/c^2$. Table 1 summarizes the results of $B^\pm \rightarrow (\chi_{c1}\gamma)K^\pm$ and $B^\pm \rightarrow (\chi_{c2}\gamma)K^\pm$ decays.

The mass of $X(3820)$ is near the potential model expectations for the center-of-gravity (cog) of 1^3D_J states: the Cornell [26] and the Buchmüller-Tye [27] potential, which gives $M_{\text{cog}}(1D) = 3810 \text{ MeV}/c^2$. Some models predict the mass of 3D_2 ($J^{PC} = 2^{--}$) states to be 3815-3840 MeV/c^2 [28, 29]. $X(3820)$ mass agrees quite well within the expectation. The $X(3820)$ state is likely to be the missing 3D_2 $c\bar{c}$ (ψ_2) state.

4 Summary

In the study of $B^\pm \rightarrow (\chi_{c1}\gamma)K^\pm$ and $B^\pm \rightarrow (\chi_{c2}\gamma)K^\pm$ decays, Belle observe the ψ' peak in both decay modes and other peak is found to be consistent with expectation. In $B^\pm \rightarrow (\chi_{c1}\gamma)K^\pm$, Belle find the first evidence of a narrow state having mass of $3823.5 \pm 2.5 \text{ MeV}/c^2$. This narrow state is likely to be the missing ψ_2 (3D_2 $c\bar{c}$ state) because the observed mass totally agrees with a theoretical expectation and $\chi_{c1}\gamma$ is one of the dominant decay modes. While in the search of C -odd partner of $X(3872)$, no signal is found at the current statistics and U.L. in 90% C.L. are provided.

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